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EFFECT OF COAXIAL LAPPING OF CAST-IRON PISTON RINGS ON RING PERFORMANCE

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EFFECT OF COAXIAL LAPPING OF CAST-IRON PISTON RINGS ON RING PERFORMANCE

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SUMMARY

A series of 25-hour accelerated high-output tests was run on a single-cylinder aircraft-type spark-ignition engine to determine the effect of coaxial lapping of piston rings prior to engine operation. Standard cast-iron rings were used and were tested as follows: (1) with all rings lapped, and (2) with only the oil-control rings lapped.

The results show that coaxial lapping with loose abrasive reduced both wear and scuffing. The difference was sufficiently marked to warrant investigating similar finishes produced mechanically. Surface-finish measurements showed that a change is produced in the root-mean-square profile height, maximum profile height, ridge-roughness number, and scratch pitch of the ring-surface profile as a result of coaxial lapping. The beneficial effect of these changes on ring performance may be accounted for by theory.

INTRODUCTION

The surface finish required for best operation of the cylinder barrel and the piston rings of an aircraft engine is unknown. Some combinations of piston-ring and cylinder-barrel materials require relatively rough surfaces to facilitate good run-in. Other combinations of piston-ring and cylinder-barrel materials use relatively smooth surfaces.

The object of the tests reported herein was to determine the effect on performance of lapping the cast-iron rings in the soft-steel cylinder barrel subsequently tested. This work is a phase of the problem of the selection of an assembly and running-in schedule to provide longest engine life. Lapping-in of rings is considered as a method of increasing the compatibility of the ring with the cylinder surface and thus decreasing the required running-in time and also increasing the life of the assembly.

The results reported were obtained at the Langley Memorial Aeronautical Laboratory during the summer of 1942 from accelerated high-output tests of a single-cylinder engine equipped with a standard aircraft cylinder and piston assembly. The work included tests with lapped and unlapped cast-iron rings of the type usually used in the particular combination under test.

DEFINITIONS

rms - The root-mean-square height of the profile as measured by the piezoelectric crystal type surface-finish analyzer, expressed in microinches.

maximum profile height - The distance between planes passing through the highest and lowest points of the profile, expressed in microinches.

percentage bearing area - The percentage of area of a given plane that is intersected by the surface profile. The given plane is parallel to and at a given distance from the nominal surface.

ridge-roughness number - The distance between planes of 2-percent and 50-percent bearing area, expressed in microinches. This particular roughness number was chosen because of its ease of computation. The choice of 2-percent bearing area eliminates the effect of single isolated peaks on the roughness number. The ridge-roughness number was obtained from the oscillograms taken with the surface-finish analyzer. The axial ridge-roughness number refers to the ridge-roughness number obtained from a trace in the axial direction. Similarly, the circumferential ridge-roughness number refers to the ridge-roughness number obtained from a trace in the circumferential direction.

average ridge-roughness number - The product of the axial and circumferential ridge-roughness numbers, expressed in microinches squared.

APPARATUS

A schematic layout of the test equipment used is shown in figure 1. The cylinder assembly consisted of an air-cooled cylinder operating with a $5\frac{1}{2}$-inch stroke and a 6.63 compression ratio. This cylinder has a bore of $5\frac{3}{4}$ inches and is made of chrome-molybdenum steel (SAE 4140, Brinell hardness, 298 to 320). The cylinder, piston, and piston rings were stock aircraft-engine parts. The piston was supplied with two auxiliary oil jets directed at the under side of the piston with a flow rate of 7 pounds per minute. These jets simulate the throw-off from the master-rod bearing and the oil from the crankshaft jet.

The fuel was injected into the manifold by means of a manifold injection nozzle, which had fuel delivered to it by a port-controlled fuel-injection pump. Combustion air was supplied by a separately driven blower and was heated by an electrical heater to the required temperature. A sharp-edge thin-plate orifice assembled to A.S.M.E. standards (reference 1) measured the rate of inlet-air flow. Cooling air was supplied by a separately driven blower.

Blow-by was measured by a positive-displacement gas meter connected to the crankcase breather line. In order to maintain a constant crankcase leakage, the crankcase pressure was maintained at 1/2 inch of water vacuum. Oil consumption was measured by a volume-displacement method corrected for variations in temperature.

Standard NACA test equipment was used to measure fuel consumption, speed, and torque. Surface-finish records were taken with a piezoelectric crystal type of surface-finish analyzer equipped with a root-mean-square meter. This analyzer records measurements in microinches, rms.

The apparatus used for lapping consisted of a dummy piston of the same type as the piston used in the tests and an extension handle attached to the piston pin of the dummy piston. The rings to be lapped were placed in their respective grooves in the dummy piston; the empty grooves were filled with dummy piston rings. The rings were lapped in the cylinder, which was subsequently tested.

The lapping compound is mainly composed of silicon carbide grains dispersed in an oil binder. The grain is specified grit No. 400. When reviewed under the microscope with a calibrated eyepiece, the abrasive particles vary from 0.001 to 0.0015 inch in diameter. The abrasive particles seem to be uniform in size.

The piezoelectric crystal-type surface-finish analyzer used in this investigation was equipped with an oscillograph that enabled oscillograms of the surface profile to be taken. The electrical characteristic of the piezoelectric crystal is such that the oscillograph tracer will tend to return to the center line of the oscillogram after it is displaced. If the specimen peak is nearly flat the form of the return curve will be similar to the section of the trace a-b in figure 2(b). In addition to the root-mean-square height and maximum profile height, the surface-finish measurements contain as another parameter the ridge-roughness number which, together with the other parameters, gives an indication of the profile shape. Surface-finish measurements for the barrel were taken on the center of the thrust face. Piston-ring measurements were taken on the face 180° from the gap.

TESTS

Tests were conducted with the following ring assemblies:

1. Standard cast-iron rings - all lapped to full-face content (three compression, two dual oil control, and one scraper)

2. Standard cast-iron rings - only oil-control and scraper rings lapped

With the exception of the lapping procedure as stated in the preceding paragraph, the following was the procedure for engine assembly and operation:

1. The cylinder barrel was polished with abrasive papers of grit No. 320 and grit No. 400.

2. The rings were then coaxially lapped (lapping motion was straight up and down) in the cylinder barrel in which the rings were subsequently tested. The lapping compound used was further diluted with lard oil. The cylinders were cleaned after lapping by washing with an organic cleaning agent and then dried by directing a stream of compressed air against the cylinder walls.

3. The rings were then weighed; measurements were taken of surface finish, clearances, and bore.

4. The engine was assembled and run in for a period of $7\frac{1}{4}$ hours; the speed and the load were gradually increased.

5. The 25-hour accelerated high-output test was performed.

6. The engine was disassembled; rings were cleaned and weighed; surface-finish and bore measurements were taken.

The following schedule and conditions were adhered to for the $7\frac{1}{4}$-hour run-in period:

(a) Run-in schedule:

Run	Condition	Speed (rpm)	Time (hr)	Horsepower
1	Motor	800-1000	1/4	------
2	Power	1000	2	18
3		1500	1	32
4		1750	1	46
5		2000	1	60
6		2200	1/2	74
7		2200	3/4	82.4
8		2200	3/4	90

(b) Run-in conditions:

Spark advance, degrees B.T.C. . . . . 20 to 25
Oil temperature (starting), °F . . . . 130±10
Oil temperature (operating), °F . . . . 185±2
Maximum rear spark-plug-bushing temperature, °F 450
Downstream barrel (center of muff) temperature, °F . . 235
Fuel-air ratio . . . . 0.095±0.005

The following conditions were adhered to for the 25-hour accelerated high-output test:

Brake mean effective pressure, pounds per
square inch 250
Speed, rpm 2200
Spark advance, degrees B.T.C. 27
Downstream barrel (center of muff) temperature, °F . . 310±3
Rear spark-plug-bushing temperature, °F . . . . 520±10
Combustion-air temperature, °F . . . . 125±2
Oil-in temperature, °F . . . . 185±2
Fuel . . . . 100-octane and 3 cc tetraethyl lead per gallon
Fuel-air ratio . . . . 0.095±0.002
Duration, hours 25

In order to obtain results that could be considered representative for a particular assembly, the tests were repeated with each assembly until comparable results were obtained. In no case, however, were more than three tests run for any one assembly. The results tabulated in table 1 are an average of two tests and are considered to be representative for the particular assembly.

RESULTS AND DISCUSSION

Effects of lapping on ring performance.- The results of these tests on coaxially lapped and unlapped cast-iron piston rings are shown in tables 1 and 2 and figures 2 to 7. Tables 1 and 2 present the piston-ring weight losses and surface-finish data. Figures 2, 3, and 4 are oscillograms of the surface profile, figures 5 and 6 are photographs of the piston rings, and figure 7 is a typical performance curve. Figure 8 shows the arrangement of the rings on the piston, for convenience of reference. Photomicrographs (figs. 9 and 10) show the metallurgical structure of the piston-ring iron used in these tests.

These data show that coaxial lapping of cast-iron rings reduced the weight loss and resulted in a better surface after operation. The improved surface condition refers to the elimination of ring scuffing with coaxial lapping. This improvement is evident from a comparison of the photographs (figs. 5 and 6). The specific oil consumption and blow-by were approximately the same for both ring assemblies. Figures 9 and 10 show that the metallurgical structure consists of fine pearlite. Much of the pearlite surrounded by the steadite is in the form of dendrites. The graphite structure corresponds closely to 60 percent sizes 7 to 8, type A; and 40 percent sizes 4 to 5, type B, A.S.T.M. Designation:A247 (graphite flake size and type designation). The structure of this piston-ring iron is similar to, if not identical with, the structure in figures 1 and 2 of reference 2.

Effect of lapping and operation on surface finish.- The surface-finish measurements of the rings as received from the manufacturer show higher values of the root-mean-square profile height (rms), the maximum profile height, and the ridge-roughness number when the trace is in the axial direction as compared with the trace in the circumferential direction. Coaxially lapping the rings resulted in surface-finish parameters (rms, maximum profile height, and ridge-roughness number) of smaller values in the axial direction than in the circumferential direction. In addition to this change in the direction of roughness, lapping also resulted in a decrease in the average ridge-roughness number and a decrease in scratch pitch. The directional surface roughness of the rings produced by operation was similar to that produced by coaxial lapping. The magnitudes of the values of all the surface-finish parameters, however, (rms, maximum profile height, and ridge-roughness number) were decreased. Operation also resulted in a further reduction in the average ridge-roughness number. With the exception of the scuffed areas, the surface finish of the rings after operation was approximately the same for either assembly (lapped or unlapped). The results also show that operation reduced the root-mean-square profile height of the barrel.

Theories correlating the benefits of coaxial lapping.- Some of the changes in surface finish produced by coaxial lapping are believed to be reasons for the reduced wear. These changes are (1) the change in directional roughness, (2) the decrease of scratch pitch, (3) the decrease of average ridge-roughness number, and (4) the change in the general character of the surface as affecting boundary lubrication.

The directional roughness of the ring and cylinder surfaces produced by coaxial lapping was smoother in the direction of rubbing and was similar to that produced by engine operation. This directional roughness is believed to contribute to reduced wear because fewer surface asperities will have to be removed in the direction of rubbing before the surfaces reach their operating finish.

The oscillogram reproduced as figure 3(b) shows a decreased scratch pitch resulting from the coaxial-lapping operation. Cracks existing in the surface peaks will be more prone to increase peak wear on a surface having a small scratch pitch than on a surface having a large scratch pitch. In this way, the coaxial-lapping operation may facilitate the seating of the rings and thus accelerate the running-in process.

The working bearing area under boundary lubrication is believed to be better indicated by the product of the circumferential and axial ridge-roughness numbers rather than by either one individually, because an area is determined by two coordinates. The decreased average ridge-roughness number may thus indicate a tendency for milder boundary lubrication because there may be a greater amount of bearing area effective under boundary-lubrication conditions. This tendency for milder boundary lubrication should result in reduced wear and in an improved surface condition.

Another factor in determining the suitability of a surface to operate satisfactorily under boundary-lubrication conditions is its ability to retain and repair an oil film. Until recently the ability of a surface to retain an oil film was considered one of the main prerequisites for satisfactory boundary lubrication. It has, however, been stated recently (reference 3) that the rate of repair of a ruptured oil film on a surface will affect the rate of wear of that surface. Thus, only when the surface will be conducive to the repair of the film, can sustained operation under boundary-lubrication conditions take place.

Although the surface profile that will result in the most satisfactory operation under boundary-lubrication conditions is still a matter of doubt, Burwell's work (reference 4) provides some information on the fundamental requirements of such surfaces. Burwell showed that the finish of the surface on which an oil was spread, in addition to the surface tension and contact angle of the oil, determined its spread. He showed that, if an oil is once spread, it will stay farther spread on a rough surface than on a smooth surface. His work also showed that an oil would spread farther on a smooth surface if initially aided in one spot. Because satisfactory piston-ring lubrication probably requires a combination of oil spreading and oil repairing in order to maintain satisfactory boundary-lubrication conditions, it is possible that the coaxial-lapping operation rather than the factory turning provided the better compromise for the best operation. The problem is further complicated because piston-ring lubrication ranges from hydrodynamic lubrication to boundary lubrication at different points of the stroke. Boundary-lubrication conditions have been considered in more detail because during these conditions appreciable wear takes place.

Although the beneficial effects from coaxial lapping are mostly attributed to the change in surface finish produced by this operation, another factor that enters when cast iron is used is the property of cast iron to bring occluded graphite to the surface when it is abraded under the proper physical conditions. The occurrence of this phenomenon has been proved by electron-diffraction experiments (reference 5). This graphite acts as a lubricant under boundary-lubrication conditions and retards the wear. It is therefore possible that lapping of cast-iron rings may tend to bring occluded graphite to the surface and in this way may provide another explanation of the improved performance with lapped cast-iron rings.

General remarks.- The reason that lapping had no effect on oil consumption is believed to be due to the very efficient operation of the oil-control rings and to the fact that this particular design of flat-faced compression ring does not ordinarily contribute to a change of oil control within a 25-hour test. The extremely low values of oil consumption obtained provide evidence of this fact.

The results of these tests were so conclusively in favor of lapped surfaces that it would seem desirable to reproduce this type of surface by machine operation. If this type of surface can be satisfactorily reproduced, the ring performance with machine-produced surfaces should be compared with the performance obtained with the lapped surfaces.

CONCLUSIONS

Accelerated high-output tests of 25-hour duration on an air-cooled aircraft cylinder having a barrel made of chrome-molybdenum steel and using turned cast-iron rings showed the following:

1. Coaxial lapping reduced wear in operation.

2. Coaxial lapping reduced scuffing of cast-iron rings.

The change in surface finish produced solely by the coaxial-lapping operation is as follows:

1. The root-mean-square height, the maximum profile height, and the ridge-roughness number in the axial direction were reduced.

2. The root-mean-square height, the maximum profile height, and the ridge-roughness number in the circumferential direction were increased; the scratch pitch and average ridge-roughness number were decreased.

3. The average ridge-roughness number was decreased.

4. The direction of roughness produced by the coaxial lapping was similar to that obtained in operation.

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TABLE 1

RESULTS OF STANDARD CAST-IRON RING TESTS

Average of two tests

A. Ring Wear

Ring	Lapped	Unlapped
	Average weight loss (gram)	Average weight loss (gram)
1	0.137	0.306
2	.076	.156
3	.062	.139
4	.085	.162
5	.101	.123
6	.030	.053
Total of three compression rings	.275	.601
Total of all rings	.493	.949
Specific oil consumption, lb/bhp-hr	0.005	0.005
Blow-by, cu ft/min (uncorrected)	2.20	2.13

B. Surface-Finish Results Before and After Test

[Results in microin., rms, as measured by piezo-electric crystal type surface-finish analyzer]

	Direction of tracer movement	Lapped		Unlapped	
		Before	After	Before	After
Top ring (180° from gap)	Axial	15-30	3-9	[a]40-65	3-6
	Circumferential	30-50	10-25	[a]15-35	11-31
Barrel (thrust center)	Axial	15-30	3-7		
	Circumferential	7-20	8-13		

[a]As obtained from manufacturer (turned).

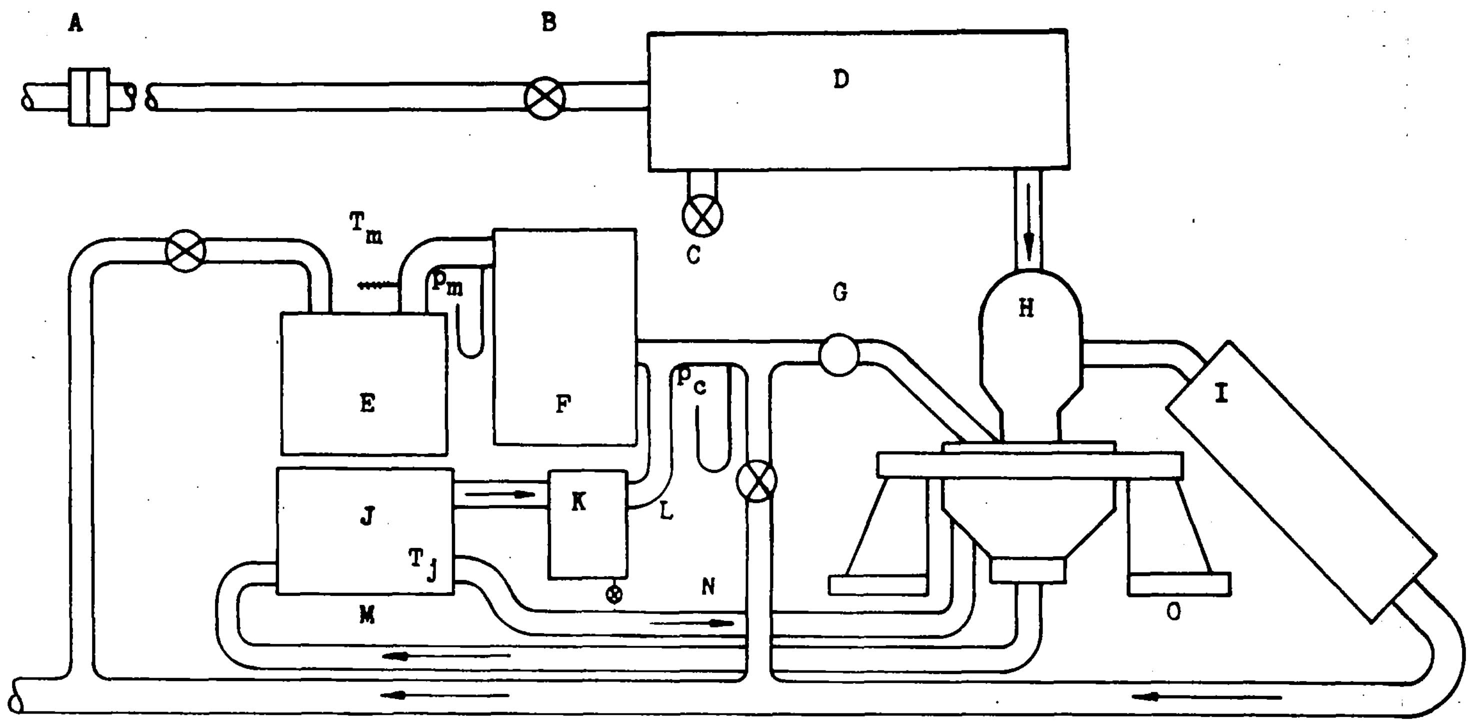
TABLE 2

SURFACE-FINISH PARAMETERS

[Results in microin.]

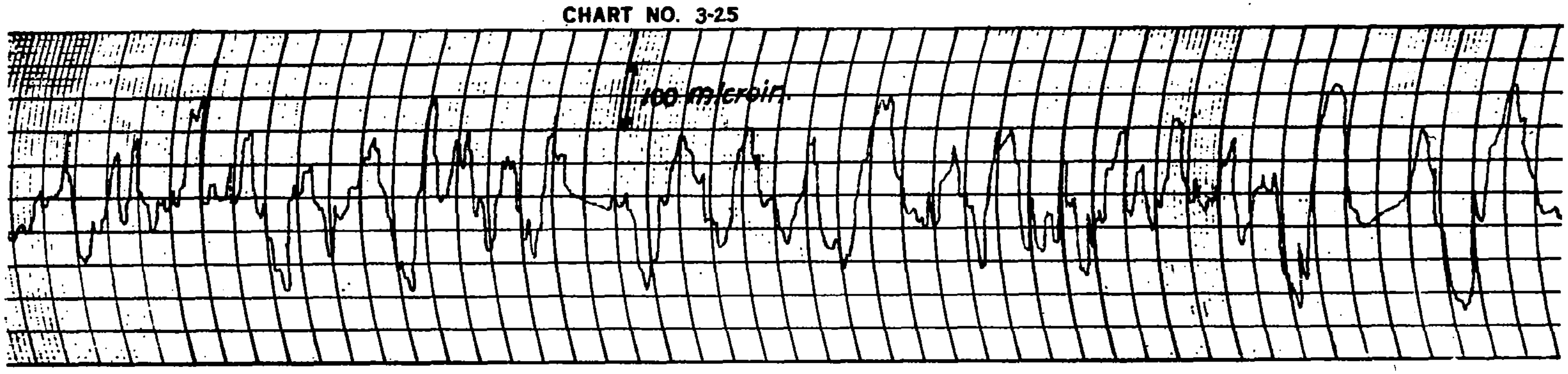
	Axial	Circumferential
Root-mean-square height, microin., rms		
Before lapping	40-60	16-27
After lapping	15-26	36-47
After operation	2-5	8-18
Maximum profile height, microin.		
Before lapping	[a]200	[a]180
After lapping	[a]120	[a]260
After operation	[a]35	[a]190
Ridge-roughness number, microin.		
Before lapping	[b]150	[b]70
After lapping	[b]50	[b]120
After operation	[b]10	[b]70
(Average[c] ridge-roughness number)^2, microin.^{2}		
Before lapping		10,500
After lapping		6,000
After operation		700

[a]±10 microin.
[b]±5 microin.
[c]The average ridge-roughness number is equal to the product of the axial and circumferential ridge-roughness numbers.

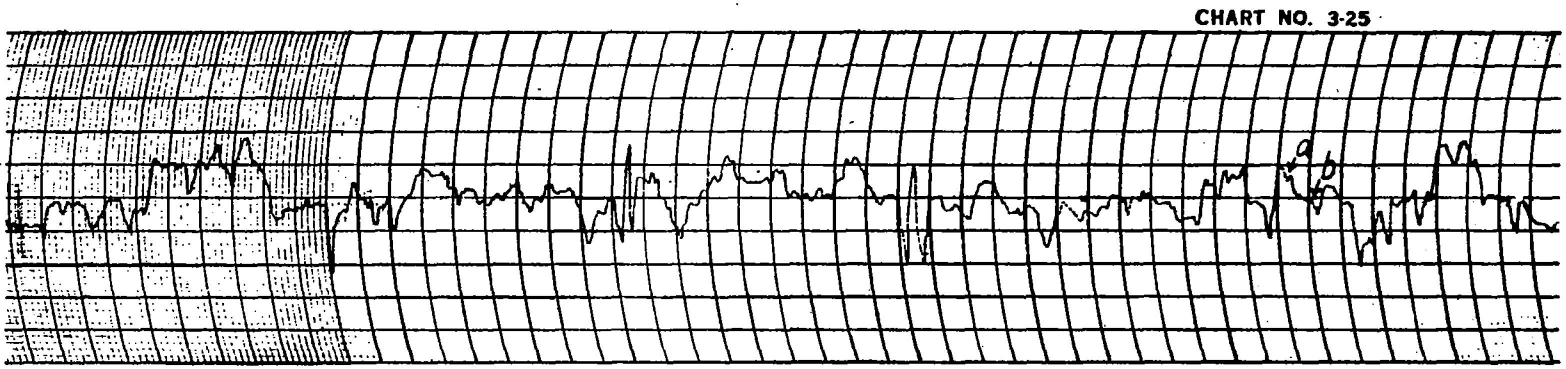


A orifice (inlet air from blower)
B throttling valve
C atmospheric relief valve
D combustion-air surge tank, 13.2 cubic feet
E blow-by gas meter
F blow-by surge tank
G sight glass
H engine cylinder, 0.0998 cubic feet
I exhaust silencer
J oil reservoir
K oil separator with drain
L scavenge-air return to blow-by system
M oil-scavenge line
N oil-supply line
O exhaust trench, 3 inches water vacuum
T_j, p_c, T_m, p_m, pressures and temperatures at points indicated

Figure 1. - Schematic layout of test equipment.

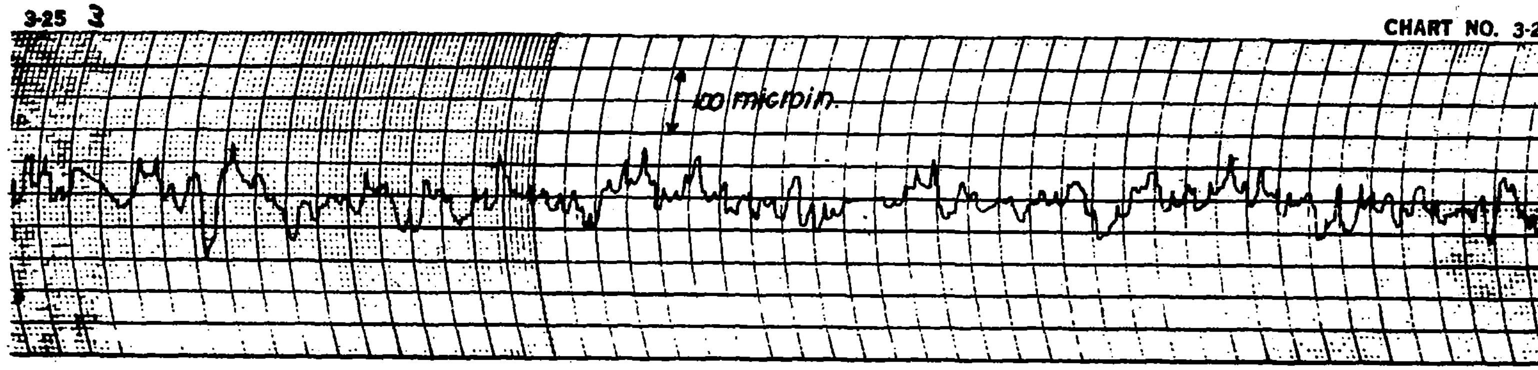


(a) Direction, axial;
vertical magnification, 4000;
horizontal magnification, 80.

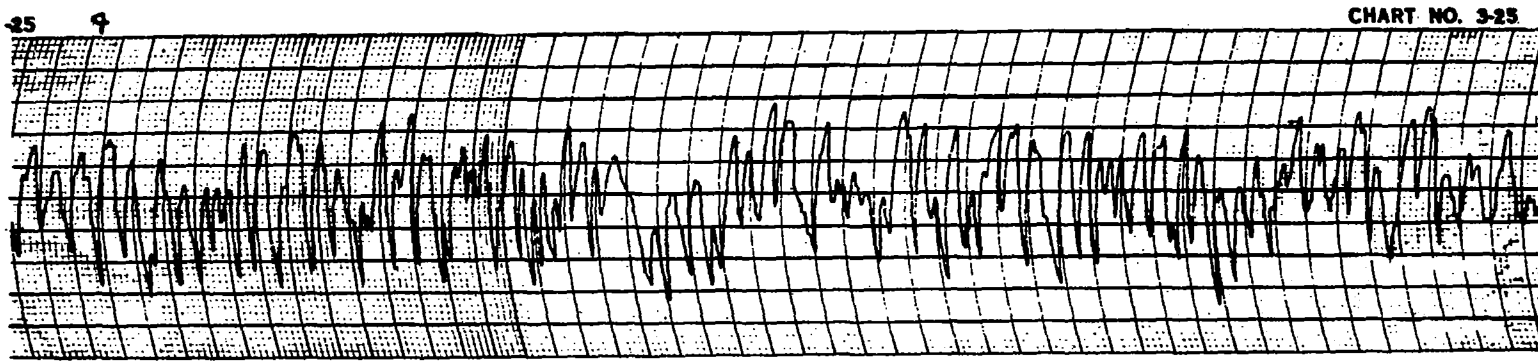


(b) Direction, circumferential;
vertical magnification, 4000;
horizontal magnification, 80.

Figure 2. - Oscillograms of the surface profile of a cast-iron ring before lapping (turned).

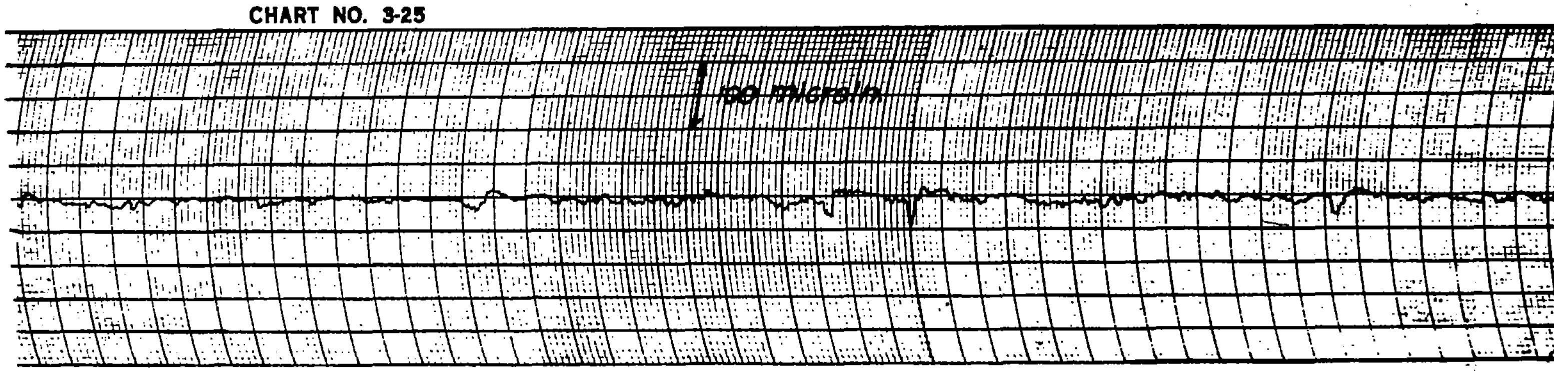


(a) Direction, axial;
vertical magnification, 4000;
horizontal magnification, 80.

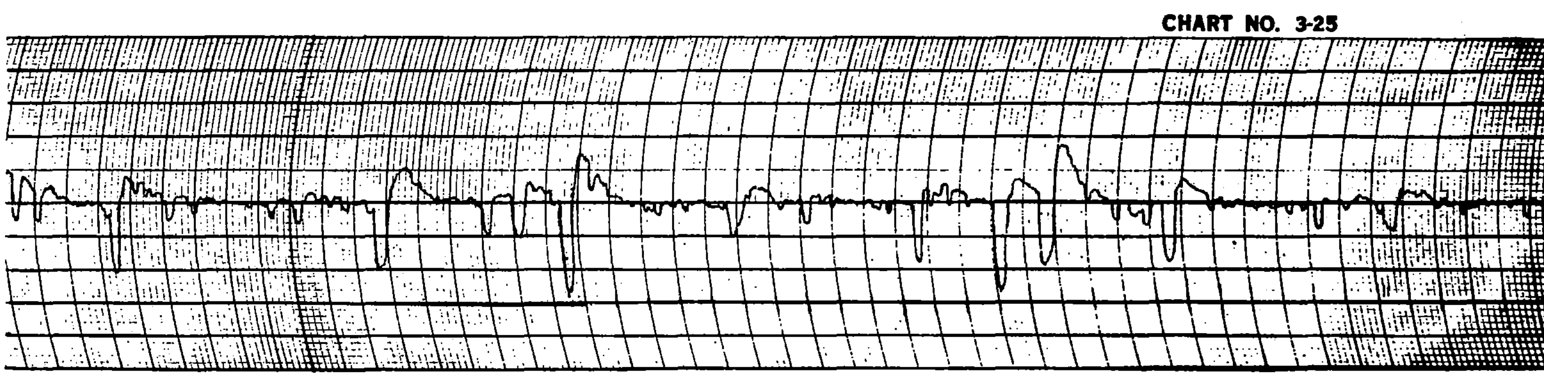


(b) Direction, circumferential;
vertical magnification, 4000;
horizontal magnification, 80.

Figure 3. - Oscillograms of the surface profile of a cast-iron ring after lapping.



(a) Direction, axial;
vertical magnification; 4000;
horizontal magnification, 80.



(b) Direction, axial;
vertical magnification, 4000;
horizontal magnification, 80.

Figure 4. - Oscillograms of the surface profile of a cast-iron ring after operation.
(Lapped and unlapped are similar.)

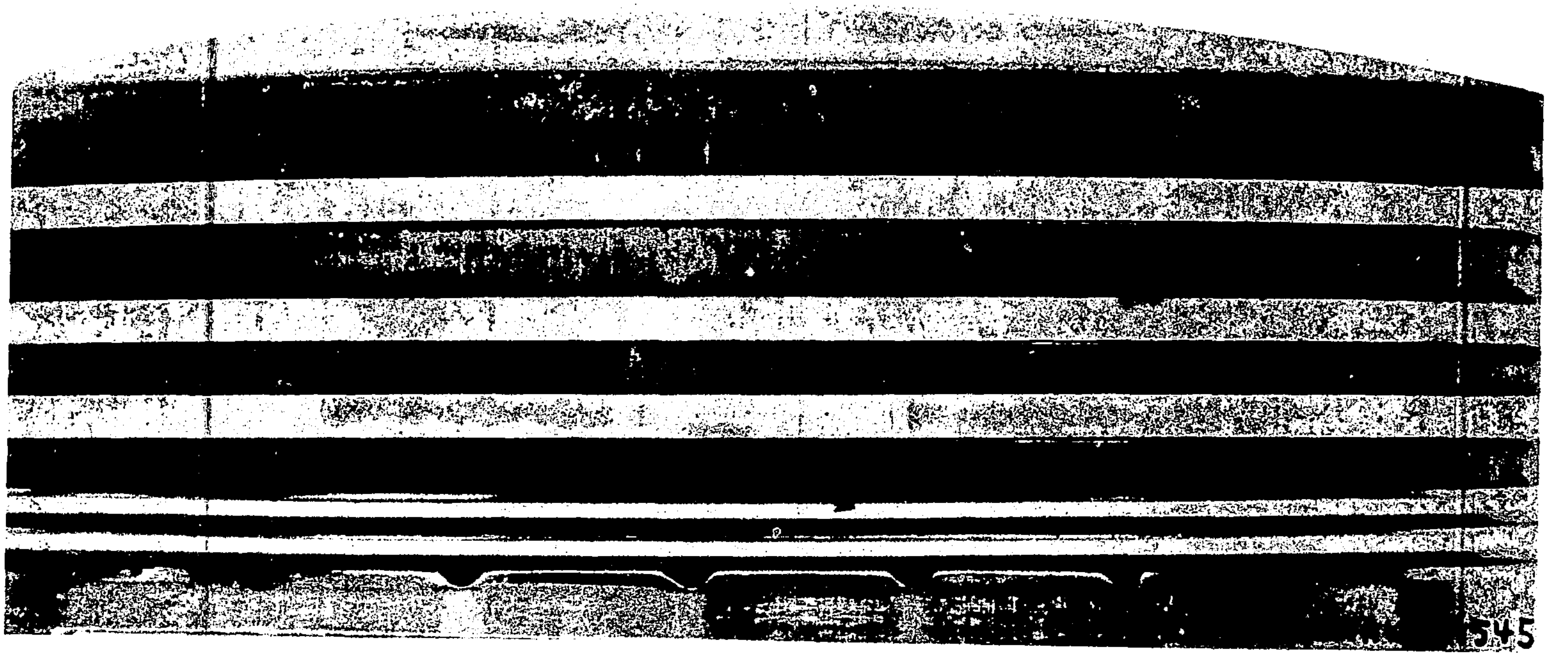


Figure 5. - Standard unlapped cast-iron rings after operation.

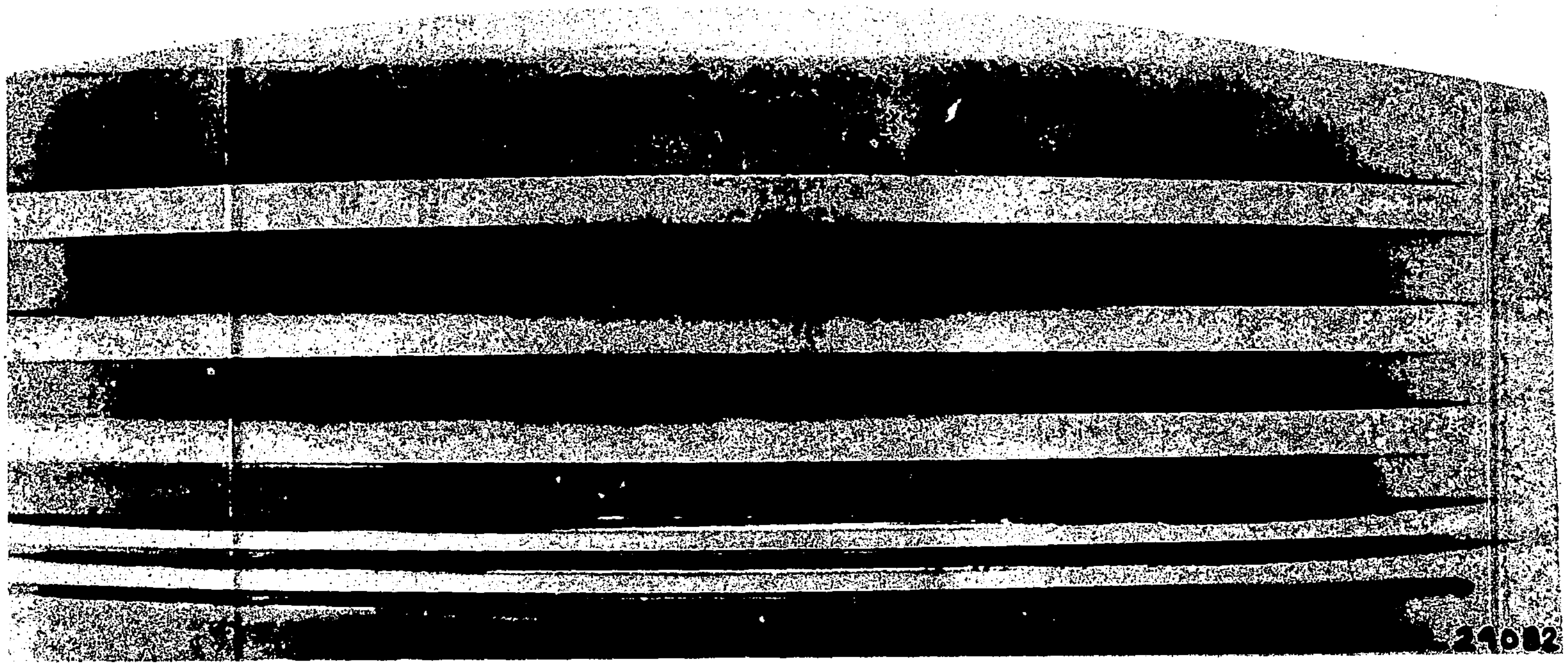


Figure 6. - Standard lapped cast-iron rings after operation.

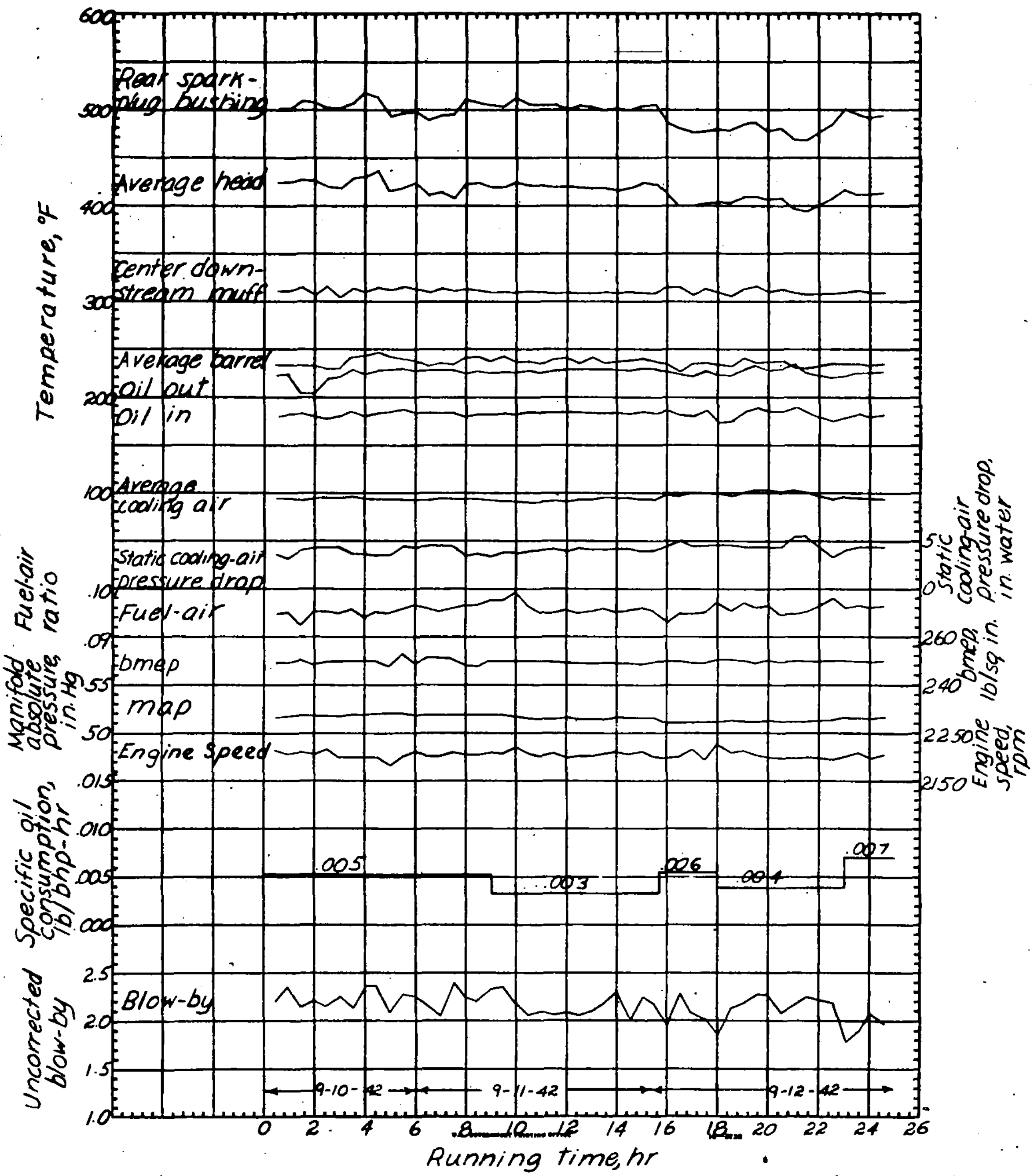
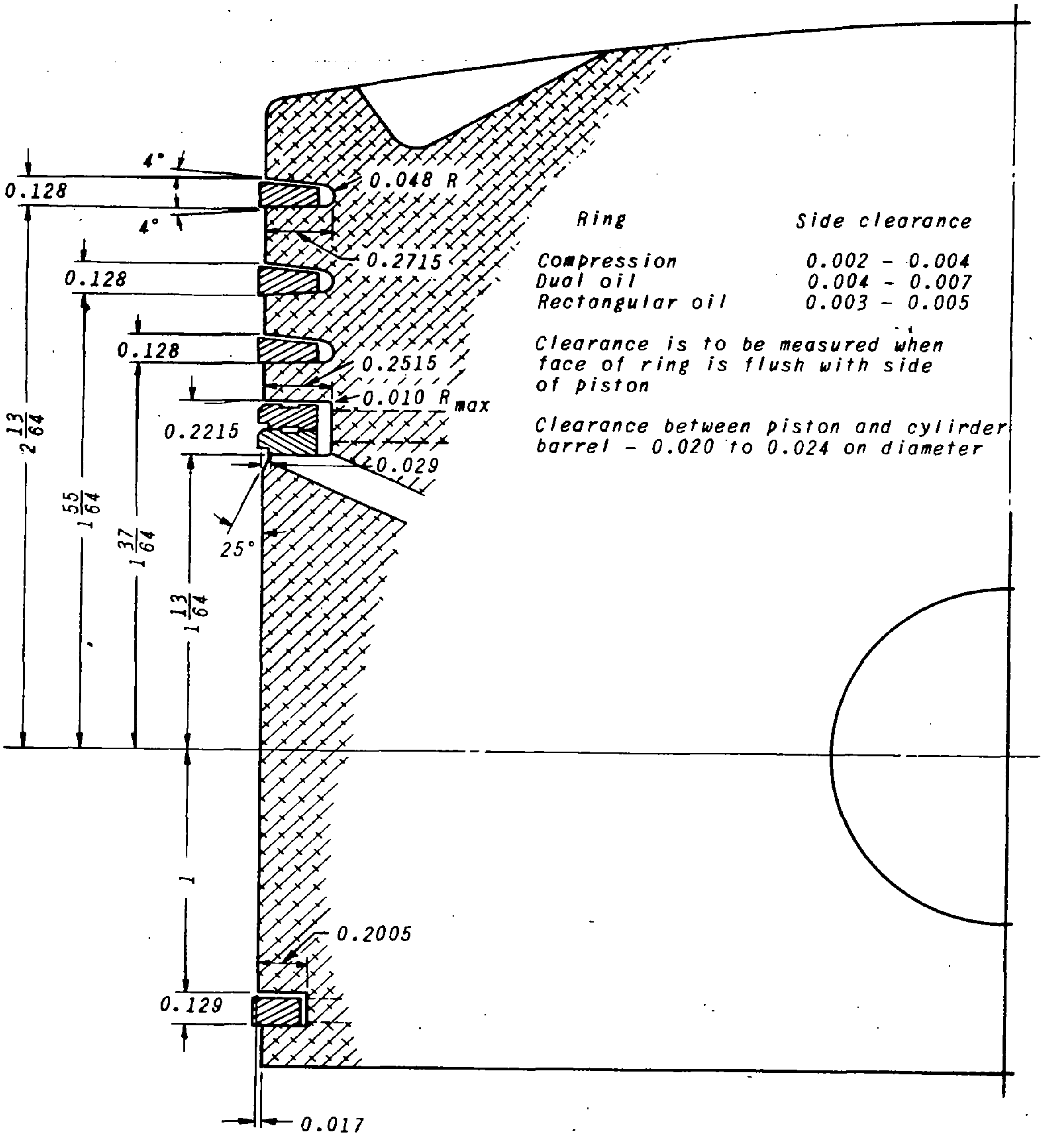


Figure 7.- Typical performance curve for the unlapped assembly



Ring	Side clearance
Compression	0.002 - 0.004
Dual oil	0.004 - 0.007
Rectangular oil	0.003 - 0.005

Clearance is to be measured when face of ring is flush with side of piston

Clearance between piston and cylirder barrel - 0.020 to 0.024 on diameter

Figure 8. - Piston-ring arrangement.
All dimensions in inches.

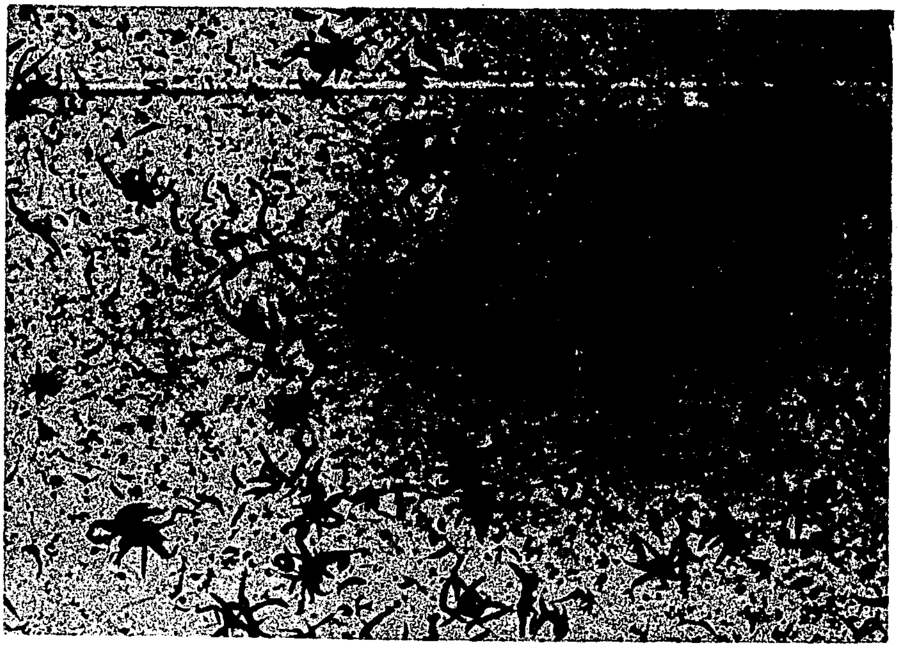


Figure 9. - Cast-iron piston-ring structure. Unetched. X100.

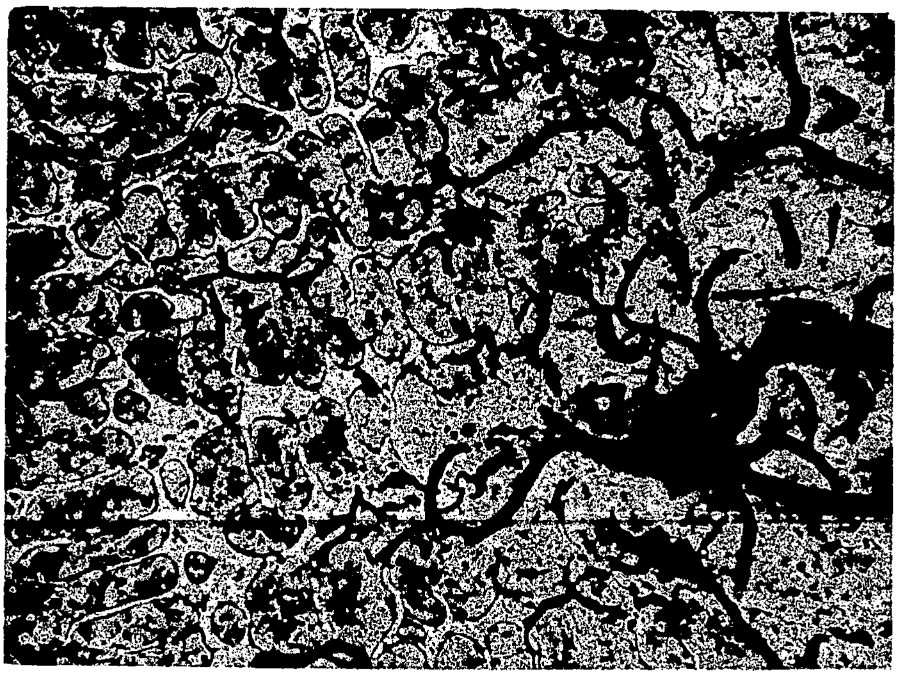


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Figure 10. - Cast-iron piston-ring structure. Etched in 2 percent nital. X500.